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We observe experimentally the transfer of angular spectrum and image formation in the process of stimulated parametric down-conversion. Images and interference patterns can be transferred either from the pump or the auxiliary laser beams to the stimulated down-converted one. The stimulated field propagates as the complex conjugate of the auxiliary laser. The phase conjugation is observed through intensity pattern measurements.

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The cavity-free stimulated down-conversion is a three-wave mixing process (TWM). TWM have been viewed as a nonlinear optical process, with promising applications for correcting wave front distortions. However, when this process was described by a quantum theory [1], a completely different viewpoint was showed. The importance of the quantum approach is closely related to the great success of the spontaneous parametric down-conversion in Quantum Optics [2] and the connection between the stimulated and the spontaneous processes. The quantum properties of the stimulated emitted light has not yet been subject of intense investigation. Previous works show that it has coherence properties of thermal and coherent states [1,3], but its individual quantum state was never put forward.

In this work, we study experimentally the transfer of angular spectrum and image formation in the stimulated down-conversion, as predicted in Ref. [4]. It was also predicted that the stimulated field propagates as the complex conjugate of one of the input fields. The understanding of the angular spectrum transfer has allowed the observation of the phase conjugation by direct intensity measurements. Our results may have a classical counterpart (except for the spontaneous emission part) in the framework of the TWM, but they support the quantum theory of Ref. [4]. The relation between the angular spectrum of the pump, auxiliary (signal) and stimulated (idler) beams were never demonstrated so far, to our best knowledge. These relations are important because they will help us to separate the spontaneous from the stimulated emission contributions in the total idler field. That will help us to understand phase conjugation at the quantum level [5].

A laser pumps a non-linear crystal, producing twin photon pairs. Another laser is aligned with one of the down-converted modes so that they overlap. The second laser, which we will refer as to the auxiliary laser, will stimulate the emission in those modes that best overlap, enhancing their intensities. As a result the conjugate twin beam, which will be called the stimulated one, has its intensity enhanced and its spectral characteristics changed in the way it was discussed theoretically in

Ref. [4]. The stimulated beam is generated from the superposition of the pump and auxiliary beams, under the restrictions imposed by the phase matching on a particular non-linear medium. Its field depends on the product of the pump and auxiliary laser fields. Its angular spectrum is given by the convolution between the angular spectrum of the pump and the auxiliary lasers.

According to Ref. [4], the intensity distribution of the stimulated (idler) beam is given by:

$$I(\mathbf{r}_i) \propto \left\{ \int d\boldsymbol{\rho} |\mathcal{W}_p(\boldsymbol{\rho})|^2 + \left| \int d\boldsymbol{\rho} \mathcal{W}_p(\boldsymbol{\rho}) \mathcal{W}_s^*(\boldsymbol{\rho}) \exp \left[i|\boldsymbol{\rho}_i - \boldsymbol{\rho}|^2 \frac{k_i}{2z} \right] \right|^2 \right\}, \quad (1)$$

where $\mathbf{r}_i = (\boldsymbol{\rho}_i, z)$ is the position in the plane transverse to the idler beam propagation at a distance z from the crystal. \mathcal{W}_p and \mathcal{W}_s are respectively the pump and the auxiliary lasers transverse field distributions at the crystal and k_i is the idler wavenumber.

In our experiment, the spontaneous emission is much smaller than the stimulated one so that the first term in Eq.1 can be neglected. We are going to analyze two particular situations. In the first one, the auxiliary laser amplitude distribution at the crystal can be considered constant. Therefore, the resulting idler intensity is given by:

$$I(\mathbf{r}_i) \propto \left| \int d\boldsymbol{\rho} \mathcal{W}_p(\boldsymbol{\rho}) \exp \left[i|\boldsymbol{\rho}_i - \boldsymbol{\rho}|^2 \frac{k_i}{2z} \right] \right|^2, \quad (2)$$

This intensity distribution is the same as the pump's after it has propagated to a plane situated at a distance z from the crystal. The only difference is that the propagation goes with the idler wavevector.

In the second situation, the pump beam amplitude distribution at the crystal can be approximated by a constant. In this case, the idler intensity is given by:

$$I(\mathbf{r}_i) \propto \left| \int d\boldsymbol{\rho} \mathcal{W}_s^*(\boldsymbol{\rho}) \exp \left[i|\boldsymbol{\rho}_i - \boldsymbol{\rho}|^2 \frac{k_i}{2z} \right] \right|^2, \quad (3)$$

In analogy to the previous case, the intensity distribution of the idler should follow the auxiliary laser one after propagation to a plane situated at a distance z from the crystal. However, now it depends on the complex conjugate of the auxiliary laser field amplitude at the crystal. The above equations were derived within the Fresnel approximation. In this regime, the phase conjugation does not affect the transferred image in a simple way and it will resemble that on the auxiliary laser. However, if the Fraunhofer limit can be taken, the image will be inverted, as we shall see. In the Fraunhofer limit the phases can be written as:

$$\exp \left[i|\boldsymbol{\rho}_i - \boldsymbol{\rho}|^2 \frac{k_i}{2z} \right] \rightarrow \exp \left(i\boldsymbol{\rho}_i \cdot \boldsymbol{\rho} \frac{k_i}{z} \right). \quad (4)$$

and Eq.3 turns into

$$I(\mathbf{r}_i) \propto \left| \int d\boldsymbol{\rho} \mathcal{W}_s^*(\boldsymbol{\rho}) \exp \left(i\boldsymbol{\rho}_i \cdot \boldsymbol{\rho} \frac{k_i}{z} \right) \right|^2, \quad (5)$$

Taking the complex conjugate of the argument of the square modulus, the result remains unchanged:

$$I(\mathbf{r}_i) \propto \left| \int d\boldsymbol{\rho} \mathcal{W}_s(\boldsymbol{\rho}) \exp \left(-i\boldsymbol{\rho}_i \cdot \boldsymbol{\rho} \frac{k_i}{z} \right) \right|^2. \quad (6)$$

It is easy to see that the intensity profile of the idler beam will have the same shape as the auxiliary laser one, but with $\boldsymbol{\rho}_i$ replaced by $-\boldsymbol{\rho}_i$. That is to say, the image on the idler beam is inverted with respect to that on the auxiliary laser beam.

A sketch of the experimental set-up is shown in Figs.1 and Fig.2. The vertically polarized He-Cd laser pumps a BBO crystal. Spontaneous parametric down-conversion takes place and twin photons converted from the pumping wavelength 442nm, to the signal 845nm and idler 925nm are produced. Because of the type II phase matching, the signal beam is vertically polarized and the idler is horizontally polarized. We utilize photon counting modules (EG& GSPCM-AQ151) for detecting signal and idler photons in coincidence. In the signal side of the detection, a 10nm bandwidth interference filter centered in 845nm is utilized, while in the idler side the bandwidth is 50nm centered in 920nm. This is the first step for obtaining stimulated down-conversion.

The second step is to carefully align an auxiliary diode laser with the 845nm signal beam. The diode laser wavelength can be tuned from 840 to about 850nm, by temperature and current control. When the alignment is good enough, the intensity of the idler is immediately multiplied by a large factor, indicating the amplification of the emission in this particular mode. The factor of amplification is determined by the coupling between the auxiliary and signal down-conversion modes. In our set-up it was about 300.

The experiment consists of placing masks on the pump(or auxiliary) beam before the crystal and observing the relationship between pump(or auxiliary) and idler

intensity distributions on a plane situated at the same distance from the crystal for both beams. First, a double-slit is placed on the pump beam, about 15 cm before the crystal, so that its spectrum carries the information of the passage through the slits during the non-linear interaction. See Fig.1. After the crystal the double-slit interference pattern is formed on the pump beam. We have measured this pattern on a plane situated about 80cm from the crystal. This is shown in Fig. 3A. According to Eq. 2, if the field amplitude of the auxiliary laser beam can be approximated by a constant, the interference pattern of the pump beam is transferred to the stimulated idler beam. Note that, while the shape of the intensity distribution of the idler should *perfectly* (in the ideal case) follow that of the pump, the propagation of the field from the crystal to detection depends on the idler wavelength. As a result, the pattern is about two times larger than that of the pump. We have measured it also on a plane placed about 80cm from the crystal. It is shown in Fig. 3B.

In a second set of measurements, we have placed the double-slit in the path of the auxiliary laser 15cm before the crystal. The pattern formed on the auxiliary beam 80cm after the crystal is shown in Fig. 4A. Once again, the intensity pattern is transferred to the stimulated idler beam, according to Eq. 3 for a constant pump field amplitude distribution. The measured pattern for the idler beam on a plane 80cm far from the crystal is shown in Fig. 4B. The pattern follows that of the auxiliary beam without inversion of the image, because this is the Fresnel diffraction. These results show that the angular spectrum from the pump and the auxiliary lasers are transferred to the stimulated down-conversion. Note that as the double-slit is small (about 0.4mm width and separated by 0.2mm) and it is placed 15cm before the crystal, the field inside the crystal is not an image of the slits with two bright spots that illuminates the crystal during the interaction, but rather a more complicated spatial distribution.

If the angular spectrum is transferred from the pump and auxiliary lasers to the stimulated idler beam, images rather than interference patterns observed on the intensity profile of those laser beams should also be transferred to the stimulated beam. In order to test it, we have projected the double-slit image on the detection plane, when it was inserted both on the pump and the auxiliary beams. See Fig.2, where slits and the lens were inserted on the auxiliary beam. This is the simplest one-dimensional image we could utilize. The double-slits are now larger than before. For the image pattern we have utilized slits of about 1mm width separated 1 mm from each other. The pump intensity distribution in the vertical direction at the image plane is shown in Fig. 5A, when the slits and the lens are inserted on the pump beam. In Fig. 5B the transferred image can be observed at the idler stimulated intensity profile. Like before, the image formed on the idler beam is larger than that on the pump beam because of the influence of the wavelength on

the propagation. The intensity peaks were made asymmetric so that we can see how the image is transferred from the pump and auxiliary lasers to the idler beam.

The same procedure was repeated placing the slits on the auxiliary beam and obtaining its image after the crystal, through focalization by a lens. Its intensity distribution is shown in Fig. 6A. However, the image transferred to the idler stimulated beam does not exactly repeat the profile of the auxiliary beam. As the intensity of the peaks are different in Fig.6A, it is possible to see that the transferred image is inverted in Fig.6B. This is a consequence of the phase conjugation as predicted by Eq.6. Now, the focalization of the auxiliary beam inside the crystal has taken us to the Fraunhofer limit because its larger dimension ($\rho_{max} \sim 0.1mm$) is much smaller than the distance between the crystal and the detection plane ($z \sim 1m$) $\rho_{max}^2 \ll \lambda z$, with $\lambda \sim 10^{-6}m$.

We have performed other measurements, for supporting the predictions of Eq.6. A sharp blade was placed on the auxiliary beam before the crystal, so that about a half of the beam was covered by the blade. Using a lens, the image of the half beam was projected on the detection plane, placed 80cm from the crystal. The intensity distributions of the auxiliary and idler beams were measured with and without the presence of the blade. This is shown in Figs. 7A and 7B for the auxiliary and idler beams respectively. The effect of the phase conjugation is then confirmed by the displacement of the intensity peaks in opposite senses. In other words, the dark half of the beam, due to the presence of the blade, has appeared in opposite sides for the image formed on the auxiliary beam and the transferred image formed by the conjugate field on the idler beam.

The results presented above can be understood in terms of the Eq. 1. The equation says that the intensity profile of the idler stimulated down-conversion is given by the product of the pump and auxiliary lasers amplitude distributions at the crystal, propagated by a Fresnel propagator to the observation plane after the crystal. The propagation is performed through the idler wavevector as it should be, but when the pump(auxiliary) field amplitude at the crystal is constant the transverse intensity distribution of the idler will follow that of the auxiliary(pump) after propagation to the same observation plane.

We would like to emphasize two points. First, the idler intensity depends on the complex conjugate of the auxiliary field. Even though the dependence comes on the intensity, so that the square modulus of the auxiliary field is calculated, the phase conjugation has observable effects in the idler intensity. This is because the conjugation changes the propagation of the field. In the above reported case, it has been responsible for the inversion of the idler image compared to the auxiliary laser one, as it was predicted by Eq.6. However, this equation is only valid in the Fraunhofer limit, far enough from the source(crystal). In the Fresnel limit the image is not inverted because the propagation depends on

$$\exp[i|\rho_i - \rho|^2 \frac{k_z}{2z}].$$

The second point is that the theoretical treatment adopted is fully quantum mechanical, In the present work, we are not exploring the quantum aspects of the process, but it can be used to study the quantum aspects of the image formation and phase conjugation in the stimulated parametric down-conversion. In this case we should probably use weaker auxiliary beams and correlation detection schemes.

In conclusion, we have observed experimentally the transfer of the angular spectrum from the pump and auxiliary lasers to the idler beam in the process of cavity-free stimulated down-conversion. The transfer of the angular spectrum is observed through the transfer of images and interference patterns. The experimental results are in agreement with the theoretical predictions of Ref. [4].

We have also demonstrated experimentally that the idler field propagates as the complex conjugate of the auxiliary laser field, even though they are completely different modes with different wavelengths and polarizations. The demonstrated properties can lead to applications where images coded by a random medium (key) may be transferred from the auxiliary beam to the idler. The decoding may be achieved by propagation of the idler through the key, for example. They have also shown to be useful for studying the process of phase conjugation at the quantum level.

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FIG. 1. Sketch of the experiment. P is the pump beam, A is the auxiliary beam S is the double-slit, C is the nonlinear crystal, D1 and D2 are detectors.

FIG. 2. Sketch of the experiment. P is the pump beam, A is the auxiliary beam S is the double-slit, L is the lens, C is the nonlinear crystal, D1 and D2 are detectors.

FIG. 3. Vertical intensity profile for A) pump beam with a double-slit inserted 15cm before the crystal and B) stimulated idler beam. Solid lines are fittings to typical double-slits pattern functions.

FIG. 4. Vertical intensity profile A) auxiliary beam with a double-slit inserted 15cm before the crystal and B) stimulated idler beam. Solid lines are fittings to typical double-slits pattern functions.

FIG. 5. Vertical intensity profile for A) pump beam when a double-slit image is focused in the detection plane 80cm after the crystal B) stimulated idler beam. Solid lines are only guides for the eye.

FIG. 6. Vertical intensity profile for A) auxiliary beam when a double-slit image is focused in the detection plane 80cm after the crystal and B) stimulated idler beam. Solid lines are only guides for the eye.

FIG. 7. Vertical intensity profile for A) auxiliary beam with(squares) and without(triangles) an inserted blade before the crystal and B) the stimulated idler beam with(squares) and without(triangles) the blade in the auxiliary. Solid lines are only guides for the eye.